TP 14538E

Light Detection and Ranging (LiDAR) – Survey of CN Rail Track near Yale, British Columbia

Prepared for
Railway Ground Hazard Research Program

by
Terrapoint Canada Inc.

October 2005

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October 2005

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Un sommaire français se trouve avant la table des matières.

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Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.	2. Project No.	3. Recipient's Catalogue No.
TP 14538E	5575	

4. Title and Subtitle	5. Publication Date
Light Detection and Ranging (LiDAR): Survey of CN Rail Track near Yale, British Columbia	October 2005
	6. Performing Organization Document No.
7. Author(s)	8. Transport Canada File No.
R. Shreenan and M. Maric	2450-DP15
9. Performing Organization Name and Address	10. PWGSC File No.
Terrapoint Canada Inc. 639 5th Avenue S.W., Suite 2400 Calgary, Alberta Canada T2P 0M9	MTB-4-01293
	11. PWGSC or Transport Canada Contract No.
	T8200-044525/001/MTB
12. Sponsoring Agency Name and Address	13. Type of Publication and Period Covered
Transportation Development Centre (TDC) 800 René Lévesque Blvd. West Suite 600 Montreal, Quebec H3B 1X9	Final
	14. Project Officer
	P. Lemay

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Co-sponsored by the partners of the Railway Ground Hazard Research Program: Natural Resources Canada, Canadian National Railway, Canadian Pacific Railway, University of Alberta, and Queen's University

16. Abstract

This project was part of an assessment of ground hazard mapping methods that rely on remote sensing techniques. It involved surveying areas along railway tracks using light detection and ranging (LiDAR), a technology that bounces laser pulses similar to radar. For this project, a LiDAR survey of 14.5 km of Canadian National Railway track near Yale, British Columbia was conducted.

The mapping survey will help produce accurate elevation data required for a digital elevation model (DEM). In conjunction with geographic information systems (GIS), researchers will be able to model various risk scenarios along the railway lines.

17. Key Words	18. Distribution Statement
Light detection and ranging, LiDAR, ground hazard mapping survey, remote sensor, laser, elevation data	Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication)	20. Security Classification (of this page)	21. Declassification (date)	22. No. of Pages	23. Price
Unclassified	Unclassified	—	xii, 26	Shipping/ Handling

Transports Canada / Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada	2. N° de l'étude	3. N° de catalogue du destinataire
TP 14538E	5575	

4. Titre et sous-titre	5. Date de la publication
Light Detection and Ranging (LiDAR): Survey of CN Rail Track near Yale, British Columbia	Octobre 2005
	6. N° de document de l'organisme exécutant

7. Auteur(s)	8. N° de dossier - Transports Canada
R. Shreenan et M. Maric	2450-DP15

9. Nom et adresse de l'organisme exécutant	10. N° de dossier - TPSGC
Terrapoint Canada Inc. 639 5th Avenue S.W., Suite 2400 Calgary, Alberta Canada T2P 0M9	MTB-4-01293
	11. N° de contrat - TPSGC ou Transports Canada T8200-044525/001/MTB

12. Nom et adresse de l'organisme parrain	13. Genre de publication et période visée
Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest Bureau 600 Montréal (Québec) H3B 1X9	Final
	14. Agent de projet P. Lemay

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Coparrainé par les partenaires du Programme de recherche sur les risques géologiques en transport ferroviaire : Ressources naturelles Canada, Canadien National, Canadien Pacifique, Université de l'Alberta et Université Queen's

16. Résumé

Ce projet s'inscrivait dans le cadre d'une évaluation de méthodes de cartographie des risques géologiques fondées sur la télédétection. Il consistait à sonder des tronçons d'une voie ferrée au moyen d'un lidar (pour *light detection and ranging*), une technologie qui émet des impulsions laser et détecte le signal rétrodiffusé un peu à la manière d'un radar. Un tronçon de 14,5 km de la voie ferrée du Canadien National près de Yale, en Colombie-Britannique, a été étudié.

Le relevé cartographique aidera à produire des données d'altitude précises, qui alimenteront à leur tour un modèle altimétrique numérique (MAN). Ce modèle, combiné au système d'information géographique (SIG), permettra aux chercheurs de modéliser divers scénarios de risque le long des voies ferrées.

17. Mots clés	18. Diffusion
Détection et télémétrie par ondes lumineuses, lidar, relevé cartographique sur les risques géologiques, télédétecteur, laser, données d'altitude	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	xii, 26	Port et manutention

ACKNOWLEDGEMENTS

The cooperation and support of Canadian National Railway are greatly appreciated in helping make this project a success. Special thanks are extended to the following CN personnel who formed part of the project team:

Gordie Basra
Tim Keegan
David Wilson
Mario Ruel

106-04125/

EXECUTIVE SUMMARY

This project was initiated in response to research related to railway ground hazards such as rock falls, landslides, snow avalanches and floods along railway corridors. The track in question, near Yale, British Columbia, was chosen as a test site to evaluate light detection and ranging (LiDAR) as a mapping tool. The mapping survey was completed to help produce accurate elevation data. Using a digital elevation model (DEM), cut and fill quantities can be estimated during the analysis process. The DEM can then be used in conjunction with a geographic information system (GIS) to enable researchers to model various scenarios along the railway lines.

The survey was conducted on June 23, 2005. Operations took place from Chilliwack Municipal Airport in British Columbia. All required data was collected in one mission and all quality control was performed onsite before the aircraft and crew were released. Data was processed in the Calgary processing office.

SOMMAIRE

Ce projet est issu d'une recherche sur les risques géologiques en transport ferroviaire, soit les éboulements, glissements de terrain, avalanches et emportements par les eaux susceptibles de survenir dans les corridors ferroviaires. La voie ferrée située près de Yale, en Colombie-Britannique, a été choisie comme site d'essai pour l'évaluation du lidar (détection et télémétrie par ondes lumineuses, ou *light detection and ranging*) en tant qu'outil de cartographie. Ce relevé cartographique avait pour but la collecte de données d'altitude précises, en vue de la création d'un modèle altimétrique numérique (MAN), à l'aide duquel il est possible d'estimer les quantités de déblais et remblais. Le MAN peut alors être utilisé de concert avec un système d'information géographique (SIG) pour modéliser divers scénarios de risque le long des voies ferrées.

La reconnaissance a été réalisée le 23 juin 2005. Les travaux ont été menés depuis l'aéroport municipal de Chilliwack en Colombie-Britannique. Toutes les données nécessaires ont été colligées en une seule mission et tout le contrôle de la qualité a été effectué sur place, avant que l'avion et l'équipe ne soient libérés. Les données ont été traitées au centre de traitement de Calgary.

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GLOSSARY

AGL	Above Ground Level
ALTMS	Airborne Laser Terrain Mapping System
ANSI	American National Standards Institute
ATC	Air Traffic Control
CGVD28	Canadian Geodetic Vertical Datum of 1928
CN	Canadian National Railway
CRAGS	Centre for Risk Assessment and Geohazard Studies
DAQ	Data Acquisition
DEM	Digital Elevation Model
DTM	Digital Terrain Model
DVD	Digital Versatile Disc
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
GPS	Global Positioning System
HT20	Height Transformation of 2000 (Canadian Geoid Model)
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LiDAR	Light Detection And Ranging
MSL	Mean Sea Level
NAD83	North American Datum of 1983
NASA	National Aeronautics & Space Administration
ND	Neodymium
NGS	National Geodetic Survey
NMAS	National Map Accuracy Standard
NTS	National Topographic System
PC	Personal Computer
PDOP	Positional Dilution of Precision
QA	Quality Assurance
QC	Quality Control
RGHRP	Railway Ground Hazard Research Program
RMSE	Root Mean Square Error
TIN	Triangular Irregular Network
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

1. INTRODUCTION

This project was conducted under the Railway Ground Hazard Research Program (RGHRP), a five-year initiative to develop risk management solutions to improve safety and reduce losses from ground hazard incidents on Canadian railways. Specifically, this research is aimed at mapping, analyzing, forecasting, and mitigating natural hazards that affect railway safety.

One of the RGHRP research areas consists of reviewing and assessing existing ground hazard mapping methods, and developing new or modified ones to meet specific needs of the railway industry. Light detection and ranging (LiDAR), a technology that transmits laser pulses and detects the backscattered signal, was identified by the RGHRP technical committee as a promising remote sensing mapping technique. Terrapoint Canada was contracted to conduct a survey of a Canadian National Railway (CN) corridor in British Columbia to verify the validity and effectiveness of the technique.

The mapping survey helped produce accurate elevation data. Using a digital elevation model (DEM), cut and fill quantities were estimated during the analysis process. The DEM will be used in conjunction with geographic information systems (GIS) by researchers at the University of Alberta's Centre for Risk Assessment and Geohazard Studies (CRAGS) and at Queen's University to model various natural hazard scenarios along railway lines.

2. PROJECT OBJECTIVE

The objective of this project was to survey two areas along CN tracks totalling 14.5 linear kilometres using LiDAR technology. The test area was located between mile markers 5 and 10 and between mile markers 14 and 18 of CN transcontinental mainline near Yale, British Columbia. A diagram showing the test sections is shown in Figure 1.

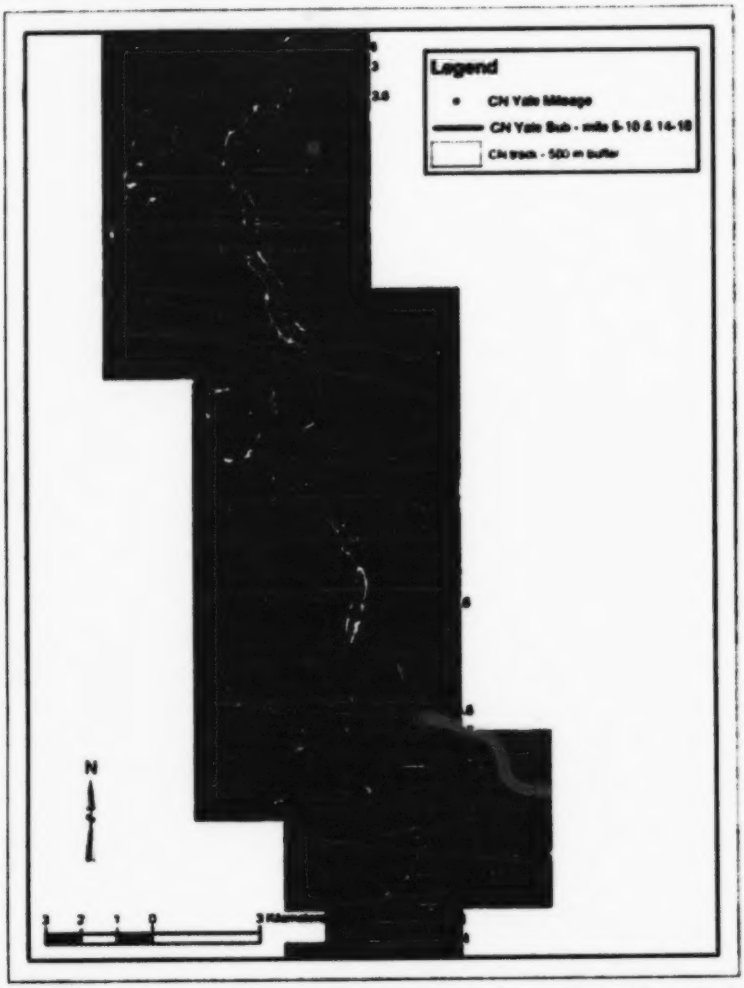


Figure 1 Project Location near Yale, British Columbia

3. METHODOLOGY AND APPROACH

The survey was conducted using one of Terrapoint's airborne laser terrain mapping systems (ALTMS). The system consisted of a state-of-the-art laser, a global positioning system (GPS), and an inertial measurement unit (IMU). Terrapoint mobilized from its Calgary base of operations to perform the LiDAR acquisition.

The following sections describe the system used for data acquisition and processing operations, and outline each step in the Terrapoint LiDAR data value chain, including quality control (QC) steps.

3.1 ALTMS LiDAR System

Terrapoint chose to build its own LiDAR system. One critical advantage of this strategy is that it enabled complete control of operations, maintenance, support and backup systems. Terrapoint's experienced engineering staff was able to optimize the proprietary sensor performance for diverse applications ranging from the frozen north slope of Alaska, USA, to the triple canopy rain forest of Congo, Africa.

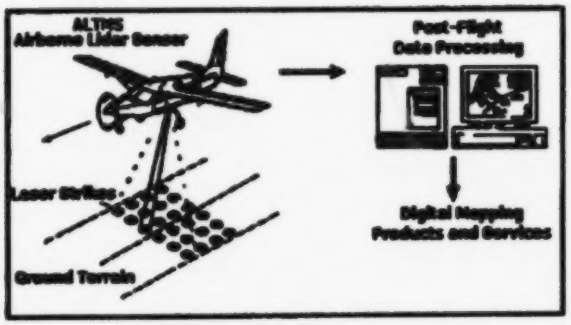


Figure 2 ALTMS Laser Scan Pattern

Perhaps the most fundamental design choice in developing a LiDAR system is the selection of a scanning mirror technology and the resulting data acquisition scan pattern. Ideally, the scan pattern would produce a raw data point spacing that is identical to the pattern of the final processed data points, thereby eliminating interpolation errors. In the GIS environment, standard DEM and digital terrain model (DTM) formats use uniform, square point spacing. Unfortunately, commercially available LiDAR systems are based on oscillating mirrors that produce a sinusoidal or "Z" shaped scan pattern with highly non-uniform point spacing.

While a sinusoidal scan pattern achieves tight crosstrack point spacing at the edges of the swath, it produces much larger crosstrack point spacing at nadir. The sinusoidal scan pattern typically produces even greater along-track spacing at the swath edges. This non-uniform point spacing is in stark contrast to the uniform, square grids used for DEM and DTM products. The non-uniform point spacing can also make it challenging to resolve the edges of stream banks, fault lines and other natural features that happen to fall in the areas covered by the wider point spacing.

Oscillating, nutating and bi-directional mirrors that produce sinusoidal scanning patterns were rejected in favour of a rotating polygon mirror design adapted from NASA technology and optimized by Terrapoint's engineers. The regular grid

point spacing most closely approximates the standard GIS formats that are used for processing and delivering the data to the customer. This minimizes interpolation errors between unequally spaced raw data points and also provides uniform point density to facilitate edge detection of natural features.

In all LiDAR systems a certain level of cropping must be done at the scan edges. In a conventional scanning system, the oscillating mirror swings, creating a convex surface formation. As with aerial photography where there are convex camera lenses, there is a "sweet spot" in the centre of the data swath and distortion at the edges. This results in high cropping angles in an oscillating system. The ALTMS polygon mirror presents a flat uniform surface to the laser and sends out an even beam all along and across the flight track. This results in a lower cropping angle and fewer points thrown out of the data.

Figure 3 demonstrates that at nadir, the ALTMS polygon scan geometry continues to send out points in a regular, uniform pattern with constant spacing both along and across the flight track. In conventional systems, the point spacing, even at nadir, is irregular with no constant distribution either along or across the flight track.

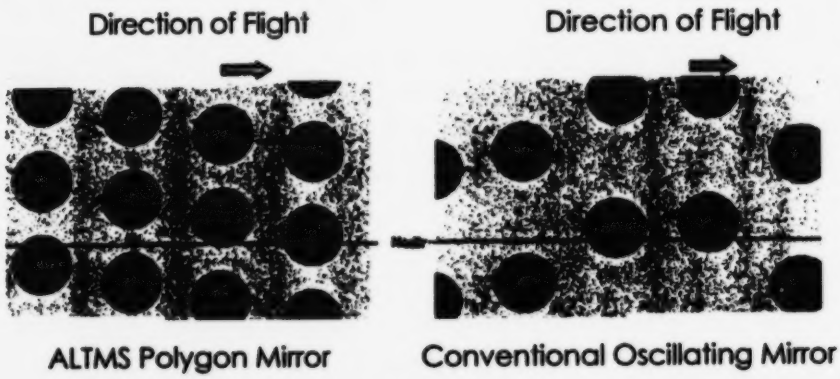


Figure 3 Comparison of the Point Spacing at Nadir - Area of Most Interest

The combined effect of these point spacing variations creates significant differences in point density produced by the two systems. The oscillating mirror scan system has a highly variable point density as a function of both crosstrack and along-track position. In contrast, the polygon mirror system produces virtually uniform point density throughout the entire swath. In addition to reducing interpolation errors, uniform point density also increases the probability of detecting naturally occurring edge type features, such as stream banks and fault lines, to improve the overall accuracy of the data set. As the final data product is a DEM or DTM grid model of the surface, which is a regular grid

pattern, it is often best to start with data that is also even and regularly spaced to increase confidence that the DEM or DTM grid cells hold an even and uniform representation of the earth's surface.

Terrapoint currently operates four fixed-wing ALTMS sensors of its own proprietary design. These sensors have been carefully optimized to conduct large area surveys and provide raw data quality that is compatible with the creation of high-accuracy DEM and DTM products.

The key technical specifications for the ALTMS are summarized in Table 1.

Table 1 ALTMS Specifications

Operating altitude	600 – 2500 m AGL
Field of view	36 deg
Scan pattern, Scan rate	Regular grid, 0-100 Hz
Laser pulse rate	0 – 40 kHz
Laser type	Diode pumped, Q-switched ND: Vanadate
Laser wavelength, ANSI Classification	1064 nm, Class IV
Pulse energy, Pulse width	0.15 mJ at 20 kHz, 10 ns
Beam divergence at exit port	0.5 – 1.0 mrad
Range measurements per laser pulse	Up to 4 (option for up to 7 ranges)
Range resolution	0.75 cm
Intensity measurements per laser pulse	1

Terrapoint used the parameters outlined in Table 2 for this project.

Table 2 Parameters for Yale Project

Operating altitude	1000 m AGL
Field of view	36 deg
Scan pattern, Scan rate	Regular grid, 100 Hz
Laser pulse rate	20 – 40 kHz
Laser type	Diode pumped, Q-switched ND: Vanadate
Laser wavelength, ANSI Classification	1064 nm, Class IV
Pulse energy, Pulse width	0.15 mJ at 20 kHz, 10 ns
Beam divergence at exit port	0.60 mrad
Range measurements per laser pulse	4
Range resolution	0.75 cm
Intensity measurements per laser pulse	1
Number of returns per square metre	~1.5

The ALTMS sensor's ability to record multiple returns from each outgoing laser pulse improves the level of detail that can be acquired in urban and forested areas. Another distinguishing feature of the ALTMS is the ability to record intensity data in addition to the range data normally acquired by LiDAR systems. The intensity

measurement is an indication of the strength of the reflected laser pulse, and is a function of the target range, size and reflectivity. Terrapoint's ALTMS system currently provides intensity data for one return from each outgoing laser pulse. Note that intensity data can be collected independent of sun angle. This permits round-the-clock operations.

3.2 Data Acquisition Operations

Field operations for the data acquisition phase of the project involved planning flight line coverage, aircraft operations, ground control and calibration as well as logistics for moving personnel and equipment in and out of the project area. The initial project planning was performed at Terrapoint's Calgary office. As the data acquisition phase began, many of the day-to-day decisions were delegated to the personnel at the project site. Terrapoint's Project Manager maintained close supervision over all activities in the field, and received progress reports outlining the current status and describing any issues that needed to be addressed.

Flight line planning was based on existing maps of the project area and on existing data sets supplemented with auxiliary information on local flight constraints. Some of the factors that were considered included ground terrain, location of cities, location of airports, and airport flight patterns. Flight lines were plotted on digitized maps so that the coordinates of the flight lines could be used in the aircraft's flight management and navigation system. Flight line profiles were generated to help the pilot and operator visualize expected flight conditions prior to the mission.

Another important function of flight operations planning is computing GPS satellite visibility models to determine flight exclusion times when there are not enough GPS satellites to track or when the PDOP (positional dilution of precision) values are out of tolerance. Terrapoint only collected LiDAR data when it was possible to track a minimum of six GPS satellites with a PDOP of less than 6.0. Due to the ever-changing satellite geometry, Terrapoint had planned to fly multiple day operations during optimum periods of GPS coverage, weather permitting. The flight operations planner scheduled flights to maximize the mission length given the constraints of PDOP, local air traffic control (ATC) operations and local terrain considerations. LiDAR flights are subject to weather restrictions, so flight planning and schedules were treated as guidelines to be followed when varying meteorological conditions were present. A total of one flight was required to capture the required data in this project.

GPS reference station locations were selected that use an existing provincial or federal geodetic control network whenever it is available and of a sufficiently high order (i.e., Order A or B) to avoid compromising the accuracy of the LiDAR

survey. The preference was for survey control where the published horizontal coordinates were determined by GPS observation and orthometric heights (elevations) were determined by precise differential leveling. Orthometric heights (elevations) were calculated from adjusted ellipsoid heights, and geoid-ellipsoid separations were determined using the geoid model adopted by the National Geodetic Survey (NGS). The variance-covariance matrix was re-scaled by the calculated a posteriori variance factor to provide a more realistic estimate of the relative precision between markers.

During LiDAR data acquisition, at least two GPS ground stations per mission are used. Typically, one is centrally located in the acquisition area (within a 30 km radius) and the second is on an adjacent control monument, which is used as an alternate if a problem occurs with the original reference station during data acquisition. In this project, two stations were centrally located to ensure baselines were kept below 20 km.

A calibration site is an area of survey control that is flown over at least once during every mission. This process helps to identify any systematic issues in data acquisition or failures on the part of the GPS, IMU or other equipment that may not have been evident to the LiDAR operator during the mission. The calibration site is ideally located in a relatively open, treeless area with several large buildings. The buildings used for calibration are surveyed using both GPS and conventional survey methods. A local network of GPS points is established to provide a baseline for conventional traversing around the perimeter of the buildings. For this project, the large hangars at Chilliwack Municipal Airport in British Columbia were used as calibration objects.

Ground truth validation is used to assess the data quality and consistency over sample areas of the project. To facilitate a confident evaluation, existing survey control is used to validate the ALTMS data. Published survey control, where the orthometric height (elevation) has been determined by precise differential leveling observation, is deemed to be suitable.

Ground truth validation points may be collected for each of the terrain categories the client requires to establish root mean square error (RMSE) accuracies for the LiDAR project. These points must be gathered in flat or uniformly sloped terrain (<20% slope) away from surface features such as stream banks, bridges or embankments. If collected, these points will be used during data processing to test the RMSEz accuracy of the final LiDAR data products. For this project, a combination of static and kinematic GPS points were collected.

A LiDAR data acquisition mission comprises a single takeoff and landing of the aircraft and sensor. Prior to each data acquisition mission, a static initialization of the onboard dual-frequency GPS receiver is conducted. If a reference station

has been established at or near the airport, which is the desired procedure, a static initialization period of at least 15 minutes provides sufficient accuracy. This ensures that cycle ambiguities can be resolved to integer values in post-processing of the GPS phase data.

The GPS static initialization is performed while the aircraft is stationary, the engines are off and the aircraft is parked away from any GPS antenna obstructions. The pilot enables internal aircraft power and permits the ALTMS operator to begin initialization of the complete LiDAR system. After ALTMS initialization is completed, the pilot starts the aircraft engines. The ALTMS operator informs the pilot when all subsequent ALTMS system checks have been completed and authorizes the pilot to proceed with takeoff. Following takeoff, the aircraft hatch or camera door is opened when the aircraft has climbed through an altitude of 600 m above ground level (AGL).

The aircraft initially flies over the selected calibration site to collect calibration data for use in post-processing. The aircraft then proceeds to the project area and the ALTMS operator selects the first flight line to be surveyed. When the aircraft is on line, the operator initiates data acquisition and the ALTMS stores the data on a removable hard disk drive. A terrain viewer formats and displays the acquired data so that the operator can monitor the data quality in real time. Multiple returns from an individual laser shot are colour-coded, giving the operator a visual indication of the penetration level through vegetation.

After all flight lines have been completed for the mission, the aircraft returns to the calibration site. This time the aircraft flies over the calibration site in the opposite direction of the first pass. Flying the site in opposing directions provides the greatest sensitivity in calculating the initial adjustment factors needed in data processing. The aircraft lands after collecting the final calibration data and returns to the location of the GPS static initialization performed at the start of the mission. Upon arrival at the static initialization point, the operator shuts down the ALTMS system, with the exception of the GPS receiver. All digital data is then burned onto DVD(s).

The ALTMS operator performs kinematic post-processing of the aircraft GPS data in conjunction with the data collected at the reference station closest to the area flown. Double-difference phase processing of the GPS data is used to achieve the greatest accuracy. The GPS position accuracy is assessed by comparison of forward and reverse processing solutions and a review of the computational statistics. Any data anomalies are identified and the necessary corrective actions are implemented prior to the next mission.

3.3 Data Processing Operations

Terrapoint has a proprietary post-processing methodology that takes the data from the ALTMS LiDAR unit and, using the calibration site and Terrapoint's overlap analysis technique, achieves the X,Y,Z raw product. In post-processing, surface values derived from LiDAR data are tested against the known ground surveyed values to determine the correct calibration parameters for each mission flown. This process immediately identifies any systematic issues in data acquisition, or failures on the part of INS, GPS or other equipment that may not have been evident to the LiDAR survey operator during the mission.

The surveyed data points for the calibration site are used in post-processing to establish a preliminary set of adjustment values for roll, pitch, yaw (heading) and range (elevation). These adjustment values compensate for systematic shifts in the data caused by slight offsets in the installation, calibration and operation of the data acquisition equipment. A preliminary value for each parameter is determined by identifying the calibration site features in the raw data and adjusting roll, pitch, yaw and range until the best fit is obtained for all roof surfaces.

All flight lines from the mission are processed using these preliminary adjustment values, and the entire data set is submitted to overlap analysis. This proprietary technique, recently developed by Terrapoint, uses a detailed statistical analysis of overlap regions throughout the mission to refine the preliminary adjustment values determined from the calibration site control points. The overlap analysis identifies common areas in adjacent flight lines that meet specific criteria such as size, flatness and slope, while ensuring that the overlapping areas contain a comparable number of points. After all the qualifying overlap areas have been identified, the adjustment values of roll, pitch, yaw, and range are optimized to minimize differences between the overlapping data sets. Additional degrees of freedom are also introduced into the optimization process to account for detailed, sensor-specific variables such as beam alignment and scan pattern. This optimization procedure improves the overall quality of the mission calibration and minimizes discontinuities between flight lines, which is particularly important in regions of steep terrain that magnify slight offsets in calibration.

In order to eliminate the effects of artifacts left in the bare-earth, the original, raw LiDAR data is processed with an automated, artifact removal technique and then followed up by manual inspection of the data. The raw LiDAR data is processed into tiles conforming to a National Topographic System (NTS) grid covering the entire project area. These tiles contain points of all-returns from the LiDAR unit and are stored in individual binary files of around 80 MB each.

Point classification or artifact removal is done using a product by Terrasolid software running on Microstation J called TerraScan. The TerraScan software uses

macros that are set up to measure the angles and distances between points to determine which classification a point should be: ground, vegetation, building, other. The angle and distance values in the macros can be varied to be more or less aggressive in the classification of points from ground to vegetation to building by varying the incidence angles and estimated distances among neighbouring points. Anything not classified as ground or error is placed into a non-ground class.

Error points are determined to be either high (spikes) or low (pits) outlier points, often beyond 3-sigma from the rest of the data set. Clouds, birds, pollution, or noise in the data can cause error points, for example.

A lower iteration angle and varying distances allow only the points with the lowest Z values to remain classified as ground. Not every minimum Z value is classified as ground. The distance and angle among points are still key factors in determining whether a point actually penetrates to the ground surface or remains higher up in vegetation or other structure. No distinction is made between ground points that hit roads or other paved surfaces versus true ground shots.

The closer an iteration angle is to 90° with a very short distance between adjacent points, the more likely a point will be classified as a building point. Building points are limited to regularly shaped, constructed structures. This includes both building structures and bridges. Road surfaces are not classified as buildings. All points that are not classified as error, ground, or buildings are classified as vegetation.

After an automated macro is run, a manual quality control (QC) effort is made to fine-tune the classification of points among the different categories. To better understand areas for improvement, points that are classified as bare earth are extracted and turned into viewable TIN and grid surfaces. These surfaces are viewed with ArcView software for inspection of areas that appear rough, artificially flattened or cut, have no data areas, or have other viewable errors.

In cleaning up ground points, effort is concentrated in areas where few ground points have been left in the bare earth model and the ground appears rough or lower and flatter than it may be in reality. The scarcity of ground points may be a result of no penetration through a dense vegetation layer, or too aggressive values with the macro. A manual inspection of these areas plays a major role in resolving any issues or irregularities with the bare earth model.

A manual effort is also made to ensure that bridges have been removed from the bare earth model or that any special features, determined by the client, are correctly identified as ground or non-ground. This special feature list can include large rock outcrops, piers and docks, levees, construction sites, and elevated roadways.

Both DEM and DTM grids are created using ESRI ArcInfo software point-to-TIN-to-grid commands. Selecting out all points that have been classified as bare earth from the TerraScan binary files and creating a TIN and grid surface create bare earth grids. Extracting out all non-error points from the TerraScan binary files and creating a TIN and grid surface from the highest elevations create highest surface grids.

As grids are created, grid cell locations are set to precisely correspond and register between the DEM and the DTM. Cell easting and northing coordinates are calculated as integer multiples of the cell size, so that adjacent tiles can be merged without re-sampling or pixel shift.

Quality assurance (QA) / QC procedures are continued through all iterations of the data processing cycle. Data passes through an automated set of macros for initial cleaning, a first edit by a trained technician, and a second review and edit by an advanced processor, and are finally exported to a final product. All final products are reviewed for completeness and correctness before delivery to the client.

RMSEz calculations for the LiDAR data set are also completed against a TIN model. The DTM is inspected in areas, and the elevation of closely spaced laser return pairs from overlapping flight swaths are compared to one another to ensure no blunders exist. The bare earth is also checked for compliance to standards under specific vegetation types. If any check points have been gathered, their RMSEz minimums may vary under different terrain types, and benchmarks need to be set for what RMSEz can be expected in each category.

As a final step for data processing, all data is exported as deliverables. Any geographic projections or datum shifts are applied to the final, edited versions of the data. The data is clipped into a tiling scheme, specified by the client, and all files are exported into the format and maximum sizes specified. Upon completion of all exports, files are randomly checked on the deliverable media to ensure transferability and the data is shipped to the client.

3.4 Quality Control for Data Acquisition

The quality control of LiDAR data and data products has proven to be a key concern by the majority of clients involved in recent LiDAR data acquisition projects. Many specifications detail how to measure the quality of LiDAR data given RMSE statistical methods. In order to meet all levels of QC concerns, Terrapoint has quality control and assurance steps in both the data acquisition phase and the data processing phase. Any acquired data sets that fail these checks are flagged for re-acquisition.

QC Step 1 – Data Acquisition (DAQ) software performs automatic system and subsystem tests on power-up to verify proper functionality of the entire data acquisition system. Anomalies are immediately investigated and corrected by the ALTMS operator if possible. Persistent problems are referred to the engineering staff, who can usually resolve the issue by telephone and/or e-mail. In the unlikely event that these steps do not resolve the problem, a trained engineer is immediately dispatched to the project site with the appropriate test equipment and spare parts needed to repair the system.

QC Step 2 – The DAQ software continuously monitors the health and performance of all subsystems. Anomalies are recorded in the System Log and reported to the ALTMS operator for resolution. If the operator is unable to correct the problem, the engineering staff is immediately notified. They provide the operator with instructions or on-site assistance as needed to resolve the problem.

The DAQ software also provides real-time terrain viewers that allow the operator to directly monitor the data quality. Multiple returns from individual laser shots are colour coded to provide the operator with an indication of the degree of penetration through dense vegetation. If any aspect of the data does not appear to be acceptable, the operator will review system settings to determine whether an adjustment could improve the data quality. Navigation aids are provided to alert both the pilot and operator to any line following errors that could potentially compromise the data integrity. The pilot and operator review the data and determine whether an immediate re-flight of the line is required.

QC Step 3 – After the mission is completed, raw LiDAR data on the removable disk drive is transferred to the Field PC at the field operations staging area. An automated QA/QC program scans the System Log as well as the raw data files to detect potential errors. Any problems identified are reported to the operator for further analysis. Data is also retrieved from all GPS reference stations that were active during the mission and transferred to the Field PC. The GPS data is processed and tested for internal consistency and overall quality. Any errors or limit violations are reported to the operator for more detailed evaluation.

QC Step 4 – The operator uses a data viewer installed on the Field PC to review selected portions of the acquired LiDAR data. This permits a more thorough and detailed analysis than is possible in real time during data acquisition. Corrupted files or problems in the data itself are noted. If the data indicates improper settings or operation of the ALTMS sensor, the operator determines the appropriate corrective actions needed prior to the next mission.

QC Step 5 – All LiDAR and GPS data is copied from the Field PC onto two separate DVDs: one for transfer to data processing, and one for local backup.

Each DVD is reviewed to ensure data is complete and readable. If any problems are detected, a new DVD is burned and checked for correctness.

3.5 Quality Control for Data Processing

QA/QC procedures for the raw LiDAR data and processed deliverables for the DEM and DTM products are performed in an iterative fashion throughout the entire data processing cycle. All final products pass through the seven-step QC check to verify that the data meets the criteria specified by the client.

Terrapoint has developed a rigorous and complete process that does everything possible to ensure data will meet or exceed the technical specifications. Experience dealing with all ranges of difficulty in all types of topographic regions has led to the development of its quality assurance methods. Terrapoint's goal is to confidently deliver a final product to the client that is as precise as possible the first time. Terrapoint will go to extraordinary lengths to make its client completely satisfied. The following list provides a step-by-step explanation of the process used by Terrapoint to review the data prior to customer delivery.

QC Step 1 – Data collected by the LiDAR unit is reviewed for completeness and to make sure all data is captured without errors or corrupted values. In addition, all GPS, aircraft trajectory, mission information, and ground control files are reviewed and logged into a database. At this time, the data will be confirmed to have been acquired using instrumentation that records first and last returns for each laser pulse, or multiple returns per laser pulse.

QC Step 2 – The LiDAR data is post-processed and calibrated for as a preliminary step for product delivery. At this time, the data is inspected for flight line errors, flight line overlap, slivers or gaps in the data, point data minimums, or issues with the LiDAR unit or GPS. Flight line swath overlap will be confirmed to have adjacent flight lines at the tolerance specified by the client for overlap throughout the project area, thus enabling an evaluation of data reproducibility throughout the areas.

This initial inspection is completed within 72 hours of receiving data from the LiDAR operators. Any errors that may only be fixed by re-flying portions of the data set are immediately found and resolved while operation crews are still mobilized and on location.

QC Step 3 – The full-featured product is reviewed as a grid and as raw points, and attention is placed on locating and eliminating any outlier or anomalous points beyond 3-sigma values. These points may be spikes (unusually high points) or pits (unusually low points). LiDAR points returning from low clouds, birds, pollution, or noise in the system can cause spikes. Pit-like tow returns can come from water

features or damp soils, or from system noise. Either type of point needs to be classified as an error point and eliminated from use by any grid products. In addition to these outliers, the full-feature product is reviewed for NO DATA points and regular looking non-surface errors like scan lines appearing in the data. Also, steps between flight lines are measured and adjusted as needed.

Unusual or odd-looking features and questionable returns are checked for validity and compared against additional source material, such as aerial photos, United States Geological Survey (USGS) digital maps, local maps, or by field inspection. Most errors found at this QC step can be resolved by re-calibrating the data set or by eliminating specific problem points.

QC Step 4 – After the full-feature data is at a clean stage, all points are classified as ground and non-ground features. Any non-regular structures or features, such as radio towers, large rock outcrops, water bodies, bridges, and piers, are confirmed to be classified into the category specified by the client for these feature types. Additional data sets, such as commercially available data sources or data sources provided by the client, may be used to assist and verify that points are assigned into correct classifications.

QC Step 5 – After the full-feature data set is certified as passing for completeness and for the removal of outliers, attention may be shifted to quality control of the bare-earth model. This product may take several iterations to reach the quality level the client is looking for. As both Terrapoint and the client inspect the bare-earth model, adjustments are made to fine-tune and fix specific errors.

Adjustments to the bare-earth model are generally made to fix errors created by over-mowing the data set along mountaintops, shorelines, or other areas of high percent slope. Also, vegetation artifacts leave a signature surface that appears bumpy or rough. Every effort is made to remove spurious vegetation values and remnants from the bare-earth model. All adjustments are made by re-classifying points from ground to non-ground or vice versa. No adjustments are made to the final grid product, as other parties cannot easily reproduce these types of adjustments from the original raw data set.

QC Step 6 – Both RMSEz and RMSExy are inspected in the classified bare-earth model and compared to project specifications. RMSEz is examined in open, flat areas away from breaks and under specified vegetation categories. Neither RMSEZ nor RMSExy is compared to orthoimagery or existing building footprints. Comparison against imagery can skew the determination of accuracy because of the lean and shadows in the imagery.

Instead, a point-to-point comparison is made of a recently acquired or existing high-confidence ground survey point to its nearest neighbour LiDAR laser return

point. This is done in the raw data set and usually with TerraScan software. The tolerance for finding a nearby LiDAR point elevation to compare to a survey point elevation is that the two points must be within a 0.5 m radius of each other in open flat areas. If no LiDAR points can be found within in this tolerance, then alternative methodologies are used to convert the LiDAR to a TIN, though this can introduce biases and processing errors in the end products and could cause the RMSE values to be skewed and fall beyond project specifications.

QC Step 7 – A final QC step is made against all deliverables before they are sent to the client. The deliverables are checked for file naming convention, integrity checks of the files, conformance to file format requirements, delivery media readability, and file size limits. In addition, as data is delivered all requested reports are delivered as they become available.

4. PROJECT OVERVIEW

4.1. Field Crew

The Terrapoint field crew consisted of a project manager and a system operator.

Aerial Services were supplied by Proflight Aviation.

4.2. Processing Crew

The project manager processed the field GPS and preliminary LiDAR point data to ensure data completeness. The system operator conducted the field LiDAR capture. Data processing was conducted by the Calgary processing team.

4.3. Size of Project

The project consisted of approximately 15 km of an existing rail corridor operated by CN.

4.4. Location

The project location was along the transcontinental mainline near Yale, British Columbia. The test area was located between mile markers 5 and 10 and between 14 and 18 (see Figures 4 and 5).

4.5. Project Type

The purpose of this project was to provide a high-quality DEM of the project area.

4.6. Duration of Project

The field data collection took place on June 23, 2005. Data deliverables were submitted on July 28, 2005.

4.7. Number of Flights

One flight was required to capture the required data. A total of approximately 25 flight lines were required to cover the project area.

4.8. Coordinate System

All horizontal data was delivered in the NAD83, UTM Zone 10, as specified by the client.

4.9. Geoid Model

Elevations were captured on the ellipsoid and concerted to the CGVD28 utilizing the Canadian Geoid HT20.

4.10. Survey Measurement Units

All survey work was done using NAD83 and products delivered in metric units. To control the survey, several control monuments were established near the project site. These control monuments were integrated into the national network by utilizing existing geodetic control near the project site. Figures 6 through 8 show descriptions of established control points.

4.11. Processing Software

The following software was used to reduce the GPS kinematic data, compute the 3-D laser points, classify and edit laser points, and transform the ellipsoidal heights to orthometric values (MSL):

- ArcView
- GrafNav/GrafNet
- Flykin
- Microstation
- TerraScan
- TerraModeler
- TerraModel
- Terrapoint's proprietary LiDAR processing software

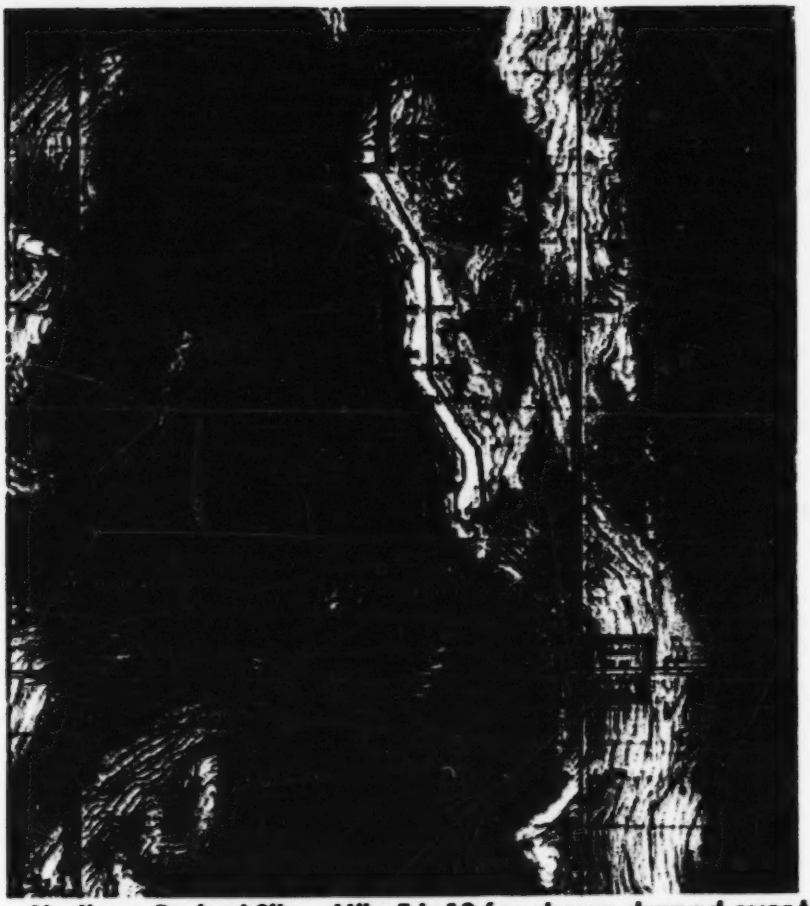


Figure 4 **Northern Project Site – Mile 5 to10 (as shown draped over topo map)**

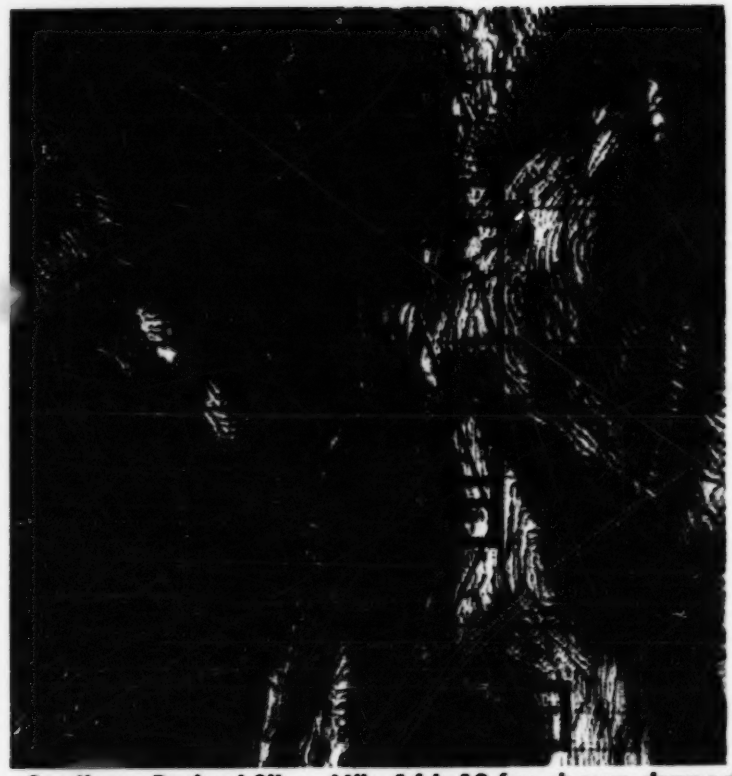


Figure 5 **Southern Project Site – Mile 14 to18 (as shown draped over topo map)**

PROJECT:	PROJECT #:	DATE:	JULIAN DAY:
Fish AC Cabin Islands	2343	23-06-2005	174
MONUMENT TYPE:	INSTALLED BY:	APPROX. LAT	APPROX. LONG
12" Spike	Mike Perdue	N 49° 45' 42.795"	W 121° 25' 43.032"

TIES	DISTANCE

Mark Name: 234301

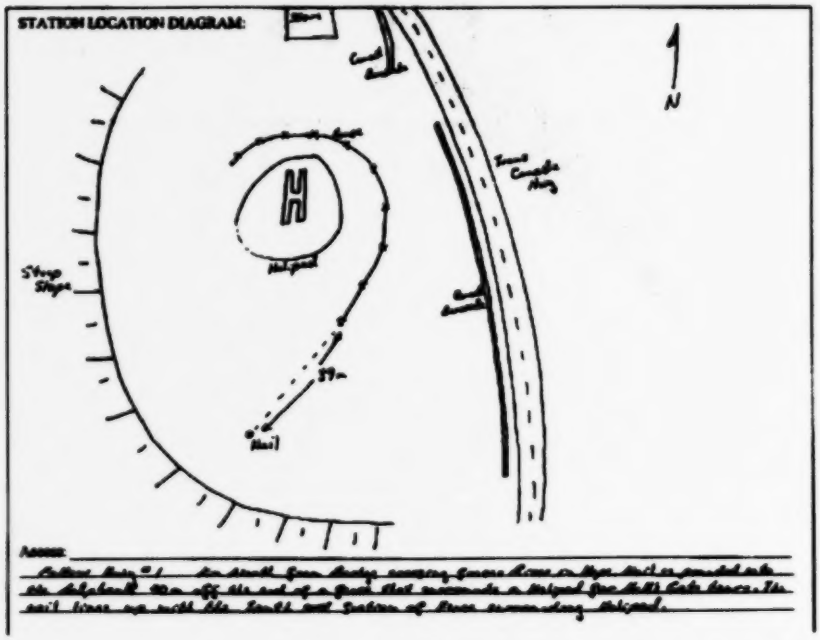


Figure 6 Description of Established Monument 234301

PROJECT:	PROJECT #:	DATE:	JULIAN DAY:
2343	Mob AC Public Mark	06-29-2005	179
MONUMENT TYPE:	**INSTALLED BY:**	**APPROX. LAT**	**APPROX. LONG**
12" Spike	Mike P / Pierce T.	41 49° 44' 42. 39° 59.510"	W 121° 25' 11.991"

TIES	DISTANCE

Mark Name: 234302

STATION LOCATION DIAGRAM:

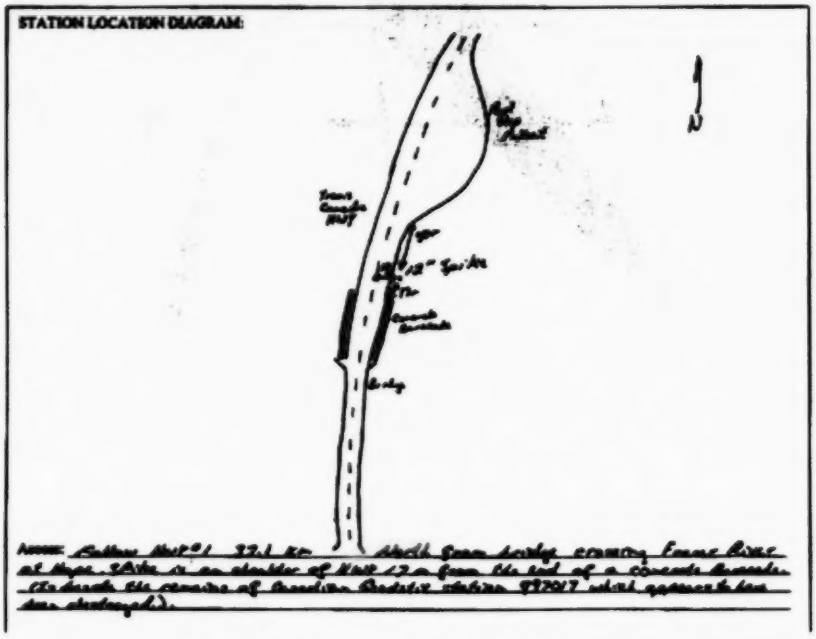


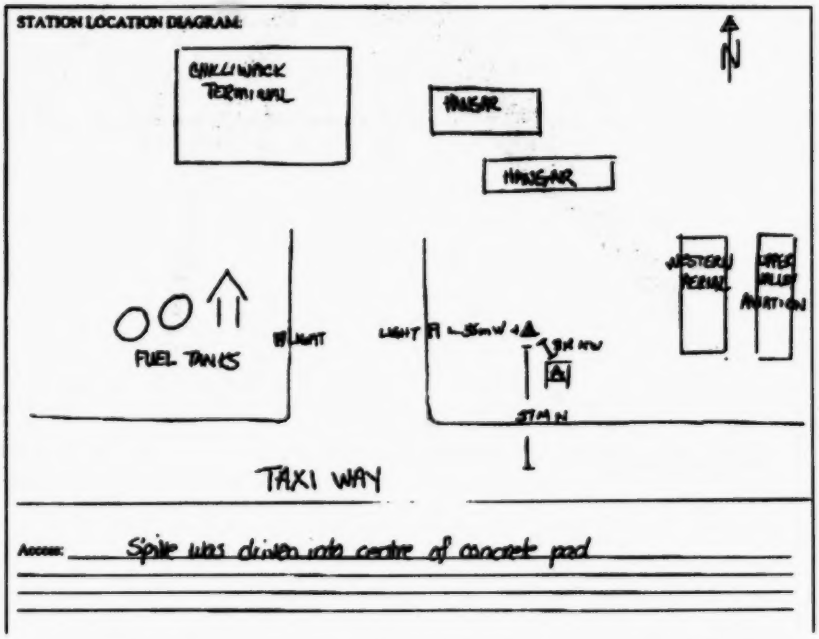
Figure 7 Description of Established Monument 234302

PROJECT: 8343	PROJECT #: 8343	DATE: June 21/05	JULIAN DAY: 174
MONUMENT TYPE: 12" spike	INSTALLED BY: Teresa	APPROX. LAT 49° 09' 19.209"	APPROX. LONG 121° 46' 33.894" W

TIES	DISTANCE

Mark Name: 234303

STATION LOCATION DIAGRAM:



Access: Spike was driven into centre of concrete pad

Figure 8 Description of Established Monument 234303

To establish accurate coordinates for monuments 234301, 234302 and 234303, national geodetic monuments were integrated into the survey. The final network is shown in Figure 9.

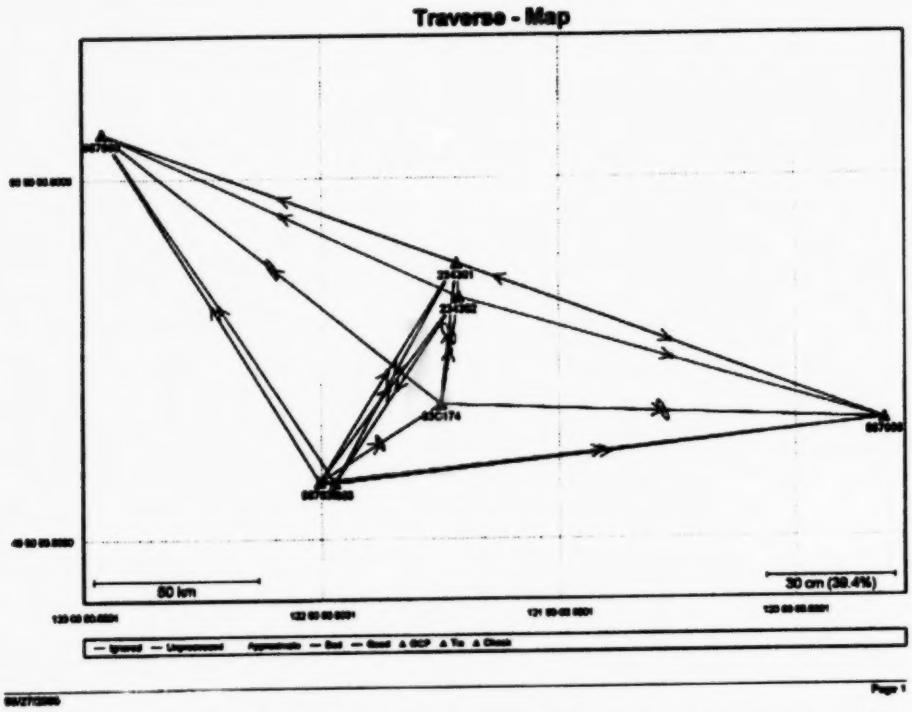


Figure 9 Control Network Diagram near Yale, British Columbia

Table 3 shows the final values of the adjusted monuments.

Table 3 Final Values of Adjusted Monuments

DATUM: NAD83

****
COMPUTED COORDINATES:
****

Station	Latitude	Longitude	Ell Ht (m)	Ref Sta	Result
234301	49 45 42.78485	-121 25 48.03802	303.199	83C174	Good
234302	49 39 59.50909	-121 25 11.98187	112.674	83C174	Good
234303	49 09 14.70760	-121 54 32.85571	-8.491	987020	Good
83C174	49 22 12.33570	-121 29 40.06950	20.198	(-)	Published (3-D)
887006	49 19 21.40910	-119 37 29.07807	542.155	83C174	Good
967000	50 07 35.52268	-122 55 16.22397	909.477	83C174	Good
987020	49 09 23.77180	-122 00 30.27630	174.357	(-)	Published (3-D)

5. HEALTH AND SAFETY

Following Terraoint's standard safety procedures (Terrapoint Health and Safety Manual Version 3.0) and contract requirements, the field crew conducted a safety meeting upon arrival at the project site and daily thereafter.

6. EQUIPMENT

6.1. Aircraft Type

A Navajo twin-engine aircraft was used for this project. The Navajo was typically flying at an altitude of 3000 ft. (915 m) AGL for the duration of the survey.

6.2. Sensor

Terrapoint's 20 kHz ALTMS was used, flying at an optimum height of 3000 ft. AGL at 140 kn. The system consists of a 36-degree full angle laser, a Trimble 4700 GPS receiver and a Honeywell H764 IMU unit. The nominal flight line spacing was 917 ft. (280 m), providing overlap of 50 percent between flight lines.

6.3. GPS Type

Two Sokkia GSR2600 dual frequency GPS receivers were used to support the airborne operations on this project.

7. ACCURACY

The following list itemizes the accuracy attainable over the project area, as a function of terrain type and vegetation cover. Note that the accuracy quoted is the accuracy of the attainable DEM, once it is processed and edited to this stage. All data accuracies quoted relate to post processed GPS/IMU/LiDAR solutions.

Accuracy is as follows, quoted at the 95% confidence level (2 sigma):

- **Absolute Vertical Accuracy**

  +/- 15-20 cm on hard surfaces (roads and buildings)
  +/- 15-25 cm on soft/vegetated surfaces (flat to rolling terrain)
  +/- 25-40 cm on soft/vegetated surfaces (hilly terrain)

- **Absolute Horizontal Accuracy**

  +/- 20-60 cm on all but extremely hilly terrain

- **Contour Accuracy**

  2 ft. (61 cm) Contour NMAS

8. DATA VALIDATION

Quality control of the data was ongoing throughout the process. Following data acquisition, GPS processing was conducted in the field to ensure completeness and integrity.

The GPS and inertial data were processed in tandem to achieve the best positional result. Once the position and attitude of the aircraft is known at each epoch (1-second intervals), the data is integrated with the laser ranges to provide a position for each data point on the ground. The data is then processed using Terrapoint's proprietary laser processing software suite to produce coordinates.

Each flight involved setting up two base stations (when possible) to collect data. Using two base stations ensures GPS data collection in the event that the main base station fails. For all flights the GPS was collected under optimum geometric configuration. This helps minimize the absolute error for the aircraft position.

The primary quality control tool for the laser ranges is the percentage of returns that are received back at the laser after it has emitted a signal. The acceptable range for returns, typically between 90 and 95 percent was met for this project. Lower percentages are normal over water and other surfaces with poor reflectivity such as dark, wet surfaces.

9. POINT GENERATION

The points are generated as TerraScan binary format using Terrapoint's proprietary Laser Postprocessor Software. This software combines the raw laser file and GPS/IMU information to generate a point cloud for each individual flight.

The bare earth is subsequently extracted from the raw LiDAR points using TerraScan in a Microstation environment. The automated vegetation removal process takes place by building an iterative surface model. This surface model is generated using three main parameters: building size, iteration angle and iteration distance.

The initial model is based upon low points selected by a roaming window and are assumed to be ground points. The size of this roaming window is determined by the building size parameter. These low points are triangulated and the remaining points are evaluated and subsequently added to the model if they meet the iteration angle and distance constraints (Figure 10). This process is repeated until no additional points are added within an iteration.

There is also a maximum terrain angle constraint that determines the maximum terrain angle allowed within the model.

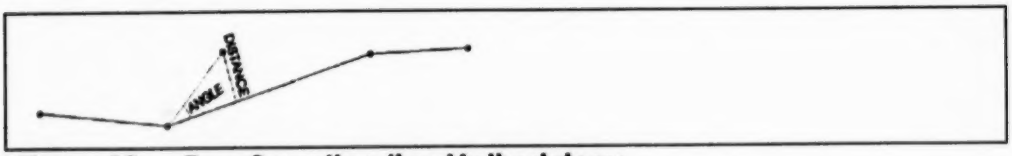


Figure 10 TerraScan Iteration Methodology
(Image Source: TerraScan User's Guide, www.terrasolid.fi)

10. PROCESSING QUALITY CONTROL

Once the data setup has been completed the manual quality control of the surface is performed. This process consists of visually examining the LiDAR points within Terrascan and correcting errors that occurred during the automated process. These corrections include verifying that all non-ground elements, such as vegetation and buildings, are removed from the ground model and that all small terrain undulations, such as road beds, dykes, rock cuts and hill tops, are present within the model.

This process is done with the help of hillshades, contours, profiles and cross sections. To correct misclassifications, a full suite of TerraScan and custom in-house data tools is used.

11. DELIVERABLES

Deliverables consisted of the following:

1. Bare Earth DEM, gridded at 1 m intervals in ASCII x, y, z format
2. Unclassified point cloud in ASCII x, y, z format for archival purposes

12. PROBLEMS, RESOLUTIONS AND CONCLUSIONS

This project was part of a RGHRP research area for reviewing and assessing existing ground hazard mapping methods, and developing new or modified ones to meet specific needs of the railway industry.

The survey of the two sections of CN tracks near Yale, British Columbia has shown that LIDAR is an effective remote sensing mapping tool. There were no problems encountered throughout the preparation, collection, processing and delivery phases of this project.

The Digital Elevation Model (DEM) is intended to be used in conjunction with geographic information systems (GIS) by researchers at the University of Alberta's Centre for Risk Assessment and Geohazard Studies (CRAGS) and at Queen's University to model various natural hazard scenarios along railway lines. Researchers at the University of Alberta have indicated that the data is already helping them to model risk scenarios.

It is recommended that LIDAR be used in other rail applications. For example, one focus of the RGHRP is to develop and test new technologies to monitor higher risk sites to detect problems before they can cause an accident. Mobile terrestrial LiDAR is an emerging technology that offers the ability to provide highly detailed and accurate digital surface models (DSMs) at a potentially lower cost compared to airborne-based LiDAR products. LiDAR-based surface models provide the potential input for several higher-order derivatives, such as rockfall mechanics process models or line-of-sight analysis.

Similarly, LIDAR could potentially be used to help measure geometric characteristics of highway-railway grade crossings as well as variations in those characteristics over time.